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Internal Acoustics of the ISS and other Spacecraft

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EXTENDED ABSTRACT

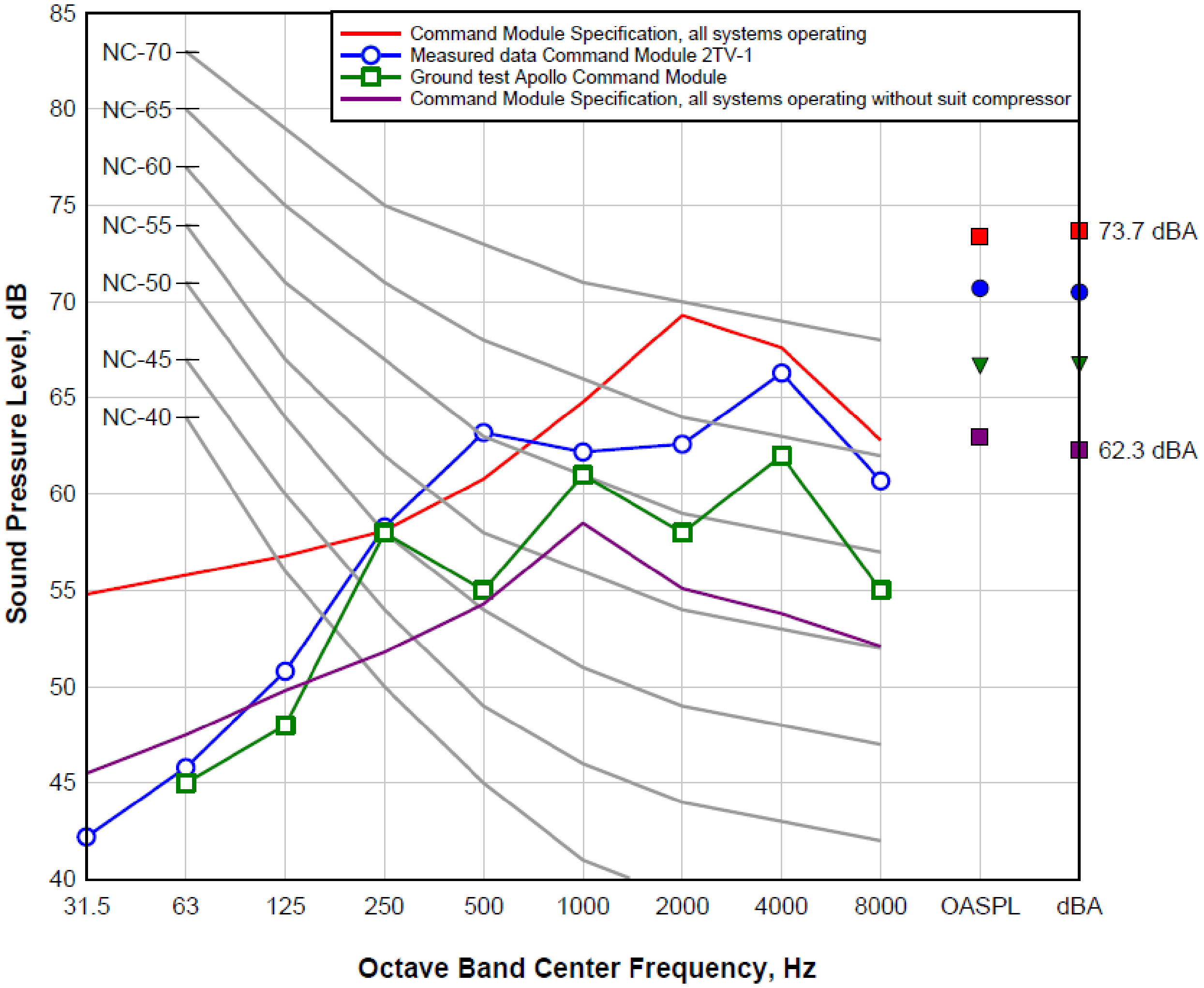
It is important to control the acoustic environment inside spacecraft and space habitats to protect for astronaut communications, alarm audibility, and habitability, and to reduce astronauts' risk for sleep disturbance, and hearing loss. But this is not an easy task, given the various design trade-offs, and it has been difficult, historically, to achieve. Over time it has been found that successful control of spacecraft acoustic levels is achieved by levying firm requirements at the system-level, using a systems engineering approach for design and development, and then validating these requirements with acoustic testing. In the systems engineering method, the system-level requirements must be flowed down to sub-systems and component noise sources, using acoustic analysis and acoustic modelling to develop allocated requirements for the sub-systems and components. Noise controls must also be developed, tested, and implemented so the sub-systems and components can achieve their allocated limits. It is also important to have management support for acoustics efforts to maintain their priority against the various trade-offs, including mass, volume, power, cost, and schedule. In this extended abstract and companion presentation, the requirements, approach, and results for controlling acoustic levels in most US spacecraft since Apollo will be briefly discussed. The approach for controlling acoustic levels in the future US space vehicle, Orion Multipurpose Crew Vehicle (MPCV), will also be briefly discussed. These discussions will be limited to the control of continuous noise inside the space vehicles. Other types of noise, such as launch, landing, and abort noise, intermittent noise, Extra-Vehicular Activity (EVA) noise, emergency operations/off-nominal noise, noise exposure, and impulse noise are important, but will not be discussed because of time limitations.

The information, herein, related to Apollo and Space Shuttle Orbiter is a synopsis of Chapters III and IV of Reference 1, written by Jerry Goodman, this author's predecessor as JSC Acoustics Office Manager, International Space Station (ISS) Acoustics System Manager, and chair of the ISS Acoustics Working Group (AWG). The information related to ISS, and Orion MPCV is taken from this authors own experiences.

For the Apollo program there were two space vehicle habitats, the Command Module (CM) and the Lunar Module (LM). It was recognized from the beginning that acoustic levels needed to be controlled. The CM and LM did have acoustic specifications, including that the Speech Interference Level (SIL), was to be 55 dB or less, to allow for adequate communications between crew and ground or between the crew. Significant noise sources included the glycol cooling pumps, cabin fans, and suit loop fan/compressor. Prior to the first crewed flight, because of crew inputs, efforts were made to reduce the noise of the glycol pump, installing vibration isolators, and flex-hoses. This was the first recorded noise mitigation effort in the Apollo program. Subsequent development testing of the CM showed the SIL to be 64 dB and 59 dB, from two separate tests. Crew comments after the first flight indicated that the cabin fans were too noisy. However, it was determined during flight that the cabin fans were not needed to run continuously, as the suit loop fan, previously considered to be the backup for the cabin fans, provided enough air flow to perform the main environmental control functions. So, instead of reducing the noise of the cabin fans, which would have cost and schedule impacts, the cabin fans were instead turned off during most of the Apollo missions. Figure 1 shows the CM specifications and measured noise levels. (Goodman, 2015)

The LM also did not meet the 55 dB SIL requirement. Again the major noise sources were the glycol pump, cabin fans, and suit loop fan. For the earliest LM missions, Apollo 9, 10, and 11, there were many complaints from the crew about the noise levels, especially the glycol pump which was said to be very irritating with a loud squeal. Even when spacesuits were worn, it was said that the noise levels inside the spacesuits was high. Hearing protection was generally used, or communication headsets with custom-molded ear insets with speakers. But the most significant issue was with sleeping in the LM with the LM on the surface of the moon. Noise along with temperature and comfort issues made for restless sleep. Measured sound levels of early LMs were 70-82 dBA, depending on location and which pump was operating. Exceedances to the 55 dB SIL were 12-20 dB. (Goodman, 2015)

In order to improve the sleeping environment for longer duration stays on the lunar surface, a significant effort was made to quiet the glycol pump. Several muffler designs were tried, including a Helmholtz resonator and several different expansion mufflers. In the end, the glycol pump noise was reduced by approximately 12 dB, resulting in sound levels of approximately 72 dBA. As a result, on Apollo 14 and subsequent lunar missions, the glycol pump noise, and the related issues with the sleep environment were reported as being much improved. (Goodman, 2015)



Source (Goodman, 2015)

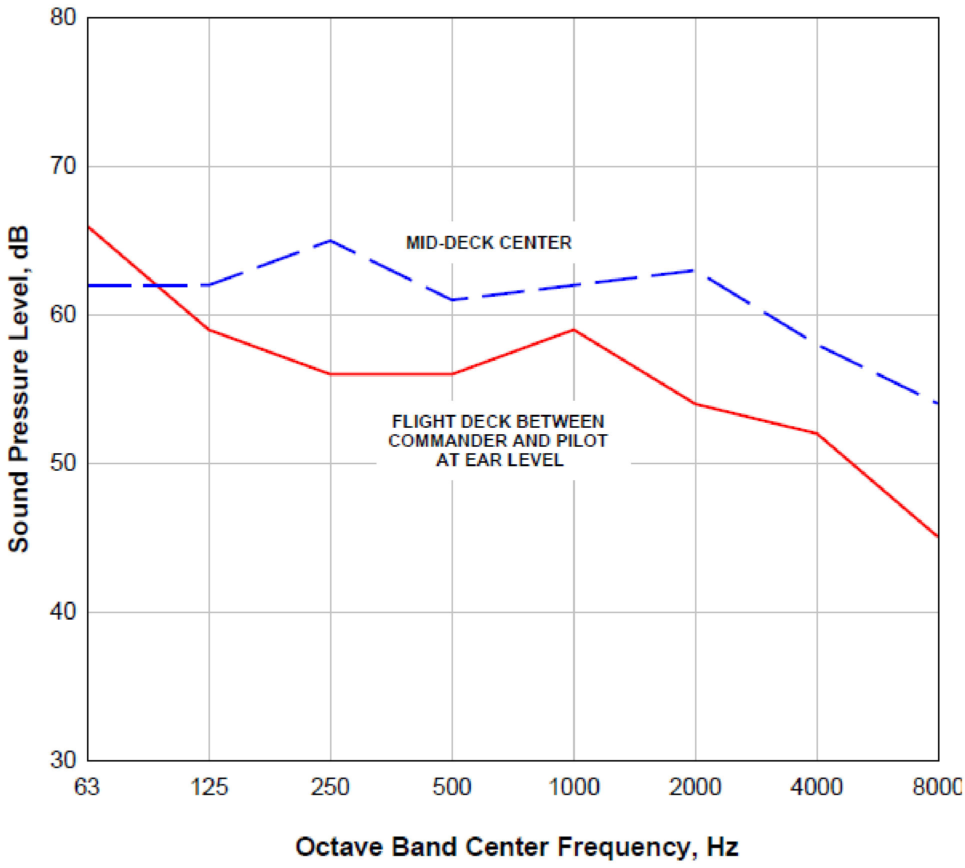
Figure 1: Apollo Command Module internal acoustic noise specifications compared to two measurements from two separate acoustic tests.

The main points for Apollo noise control were that even though there were acoustic specifications, the design approach did not include any method or checks to insure that these specifications would be met. Also, management were initially reluctant to make design changes in order to address the high acoustic levels. And, after mission impacts and crew comments convinced management to take action, only limited noise reductions were realized. It was fortunate that operational work-arounds, e.g. shutting off the CM cabin fans, and the missions' short durations, with use of hearing protection, resulted in a successful program. Following Apollo, a new design standard was implemented, including an NC-50 limit for continuous noise, and this standard impacted Space Shuttle and ISS acoustics efforts. (Goodman, 2015)

The Manned Space Flight Center (MSC) Design and Procedural Standard 145, implemented based on Apollo experience, dictated an NC-50 limit for continuous noise, as well as an NC-40 limit for continuous noise during sleep (NASA MSC, 1972). However, the prime contractor for the Space Shuttle Orbiter did not accept NC-50 as a requirement, because they thought the requirement was too stringent and was not convinced that it was necessary. Instead, NC-55 was accepted as a goal. (Goodman, 2015)

The Space Shuttle Orbiter design did include a significant effort to control noise levels. A source, path, receiver analysis was performed, with recommendations made on how best to control noise. There was a low noise fan development effort, which made progress. But, this effort was curtailed and a more powerful fan was selected for the environmental control system. Most of the effort was put into controlling the noise along its path of transmission. Many vibration isolators were utilized, to de-couple the source vibration from the structure. Absorptive duct treatment was considered, but was not implemented because of interference with close-out panels. (Goodman, 2015)

The first Orbiter vehicles, the Orbital Flight Test (OFT) vehicles, significantly exceeded the NC-55 requirements. Inlet and outlet mufflers for the noisy Inertial Measurement Unit's cooling system were developed by the National Aeronautics and Space Administration (NASA) and implemented as Government Furnished Equipment (GFE). The resulting sound pressure levels were reduced, but still exceeded NC-55. These resulting levels were accepted as the Orbiter requirement in the Orbiter Vehicle End Item Specifications (NASA, 1973), with sound levels of 68 dBA for the Orbiter's mid-deck and 63 dBA for the flight-deck. The corresponding sound pressure levels are presented in Figure 2. These levels were for the Orbiter vehicle only, payloads, and GFE hardware were considered separately. (Goodman, 2015)



Source (Goodman, 2015)
Figure 2: Orbiter mid-deck and flight deck Vehicle End Item Specification (OVEI) limits, based on measured Orbiter sound pressure levels in the Orbital Flight Test (OFT) configuration.

During the Space Transportation System (STS) -40 flight, payloads, i.e. science experiment hardware, contributed significantly to the composite acoustic environment of the Orbiter's mid-deck. These payloads did not meet their acoustic emissions requirements, but received waivers to fly on this mission. The Spacelab also flew on this mission, and exceeded its acoustic requirements. Resulting sound levels were 71 – 75 dBA in the mid-deck, and caused communications interference, annoyance, headaches, and sleep interference. Temporary hearing threshold shifts were also documented. (Goodman, 2015)

> *The communications capability within Spacelab had become obscured by the high ambient noise levels of the experiment hardware, and the crew had to move into the airlock to communicate with the ground (away from the experiments that they were operating). In Spacelab, the crew's callouts needed to be repeated. "Say again" was the phrase repeated over and over again, and the crew became very frustrated. (Goodman, 2015: IV-37)*

With Space Shuttle mission durations being 28 days or less, and with the issues experienced concerning the acoustic environment, it was clear that for the International Space Station (ISS), with mission durations of six months, that continuous noise levels would need to be lower. Once again the NC-50 criterion for continuous noise was recommended. (Goodman, 2015)

For the ISS, NC-50 was levied and accepted as the continuous noise requirement in US modules. These requirements were included in the ISS Program's "Manned-System Integration Requirements" (NASA, 2004) and were implemented in the various module-specific specifications. Noise control efforts in ISS modules were significant. The main continuous noise sources were water cooling pumps, cabin air-conditioning fans, and inter-module ventilation fans. Vibration isolation, acoustic barriers, close-out panels and absorptive treatments were used along with inlet and outlet mufflers for the fans. Prior to launch, acoustic verification testing was performed on all modules, and compared to the NC-50 requirement. In some cases, after remedial actions were taken to mitigate significant requirement exceedances, minor exceedances to the NC-50 requirement were accepted.

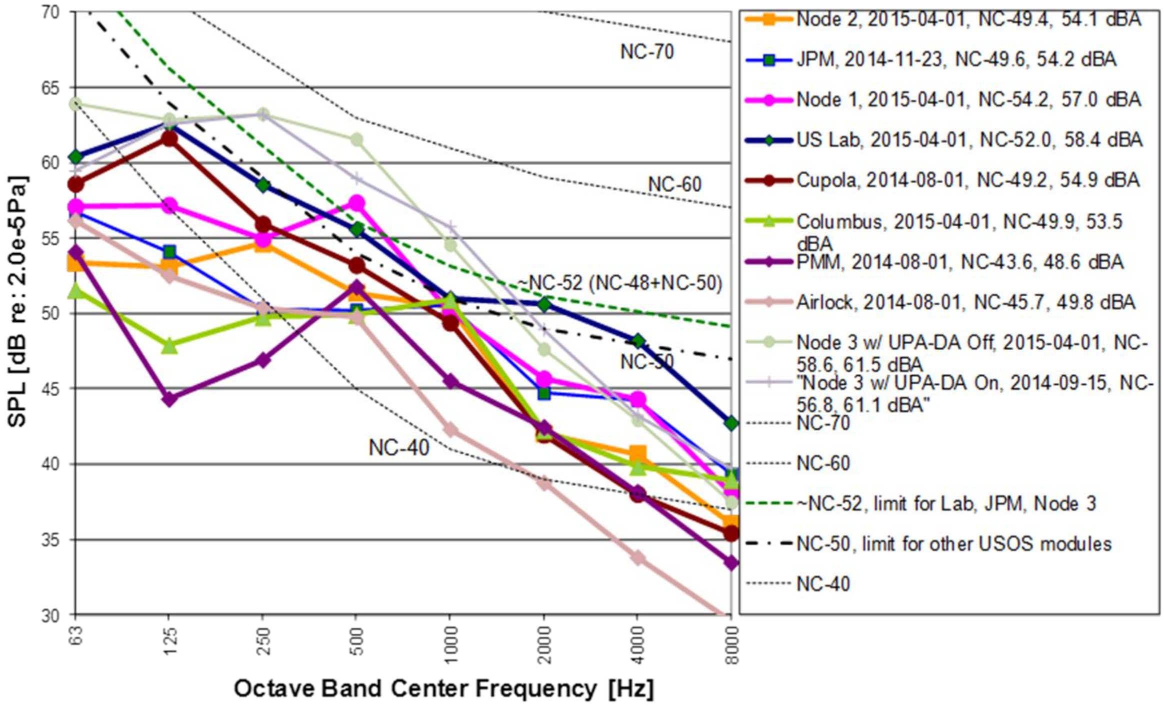
One problem with the acoustic requirements was that, in the Manned System Integration Requirements, NC-50 was meant to apply to the module with all systems operating, including payloads. However, in the ISS module specifications, the entire NC-50 requirement was given to the modules, without including the payloads. And, the number of payloads were expected to be significant.

To control the noise of payloads, a requirement of NC-48 was given to the complement of payloads in the laboratory modules, including U.S. Lab, Japanese Experiment Module, and Columbus Operating facility. Thus, the implicit requirement inside these modules became NC-50 + NC-48, where NC-50 was the module-alone contribution, and NC-48 the payload complement's contribution. The resulting requirement curve was close to the NC-52 criterion curve. After ISS "assembly complete", NC-50 + NC-48 was explicitly specified as the requirement for the module plus payload continuous noise and given the nomenclature NC~52 (Allen 2015).

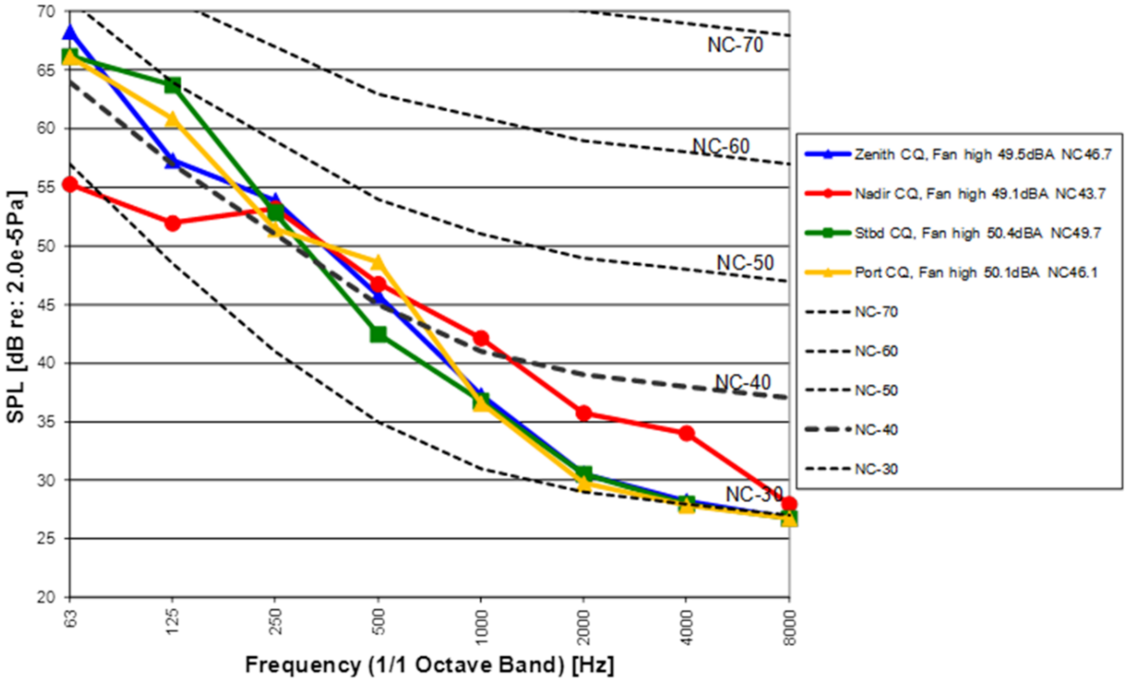
In order to control payload noise, the NC-48 complement requirement was sub-allocated down to the various payload elements. The construction of the ISS modules included rows of rack bays, where four racks could be installed radially in each bay. For example, the U.S. Lab has six rack bays so would hold 24 racks. Some payloads would take up a whole rack, and other payload facility racks could hold up to ten sub-rack payloads. In order to control the noise levels from all of this hardware, the allocation strategy required payload racks to meet an NC-40 requirement, and sub-rack payloads to meet a modified NC-32 requirement. Aisle-mounted payloads, i.e. payloads attached to rack-fronts were required to meet an NC-34 requirement. The verification location for these sub-allocated payload requirements was set to be sound pressure levels, measured two feet (0.6 m) from the loudest side of the payload. Individual payload acoustic verification was performed by test, but test-based analysis was used for verification of facility payload racks. Verification of the module's payload complement against the NC-48 requirement was also performed by analysis. And, this verification was (and still is) performed for each ISS mission, as the complement of payloads is continually changing with various science experiments being performed in the ISS' laboratory modules.

One very important feature of the ISS is its private crew quarters, which are required by the Manned System Integration Requirements for missions longer than 30 days. These crew quarters provide each crew member with a quiet environment for rest and privacy with a continuous noise requirements of NC-40 at the crewmember's head location. A significant noise control effort was made on these crew quarters in order to block out the module's noise and to control the noise of the crew quarter's ventilation fans that brought in the air from the module's cabin, circulated it throughout the crew quarter and then back out into the cabin (Broyan, 2010). Acoustic verification of the NC-40 crew-quarters were performed on the ground prior to flight, with a simulated external environment.

In addition to the ground based verification testing, and integrated acoustic analyses, on-orbit measurements of the continuous noise on ISS are also routinely performed. Sound pressure level results in the U.S. Segment modules, compared to requirements are shown in Figure 3, and similarly inside the Crew Quarters are shown in Figure 4.



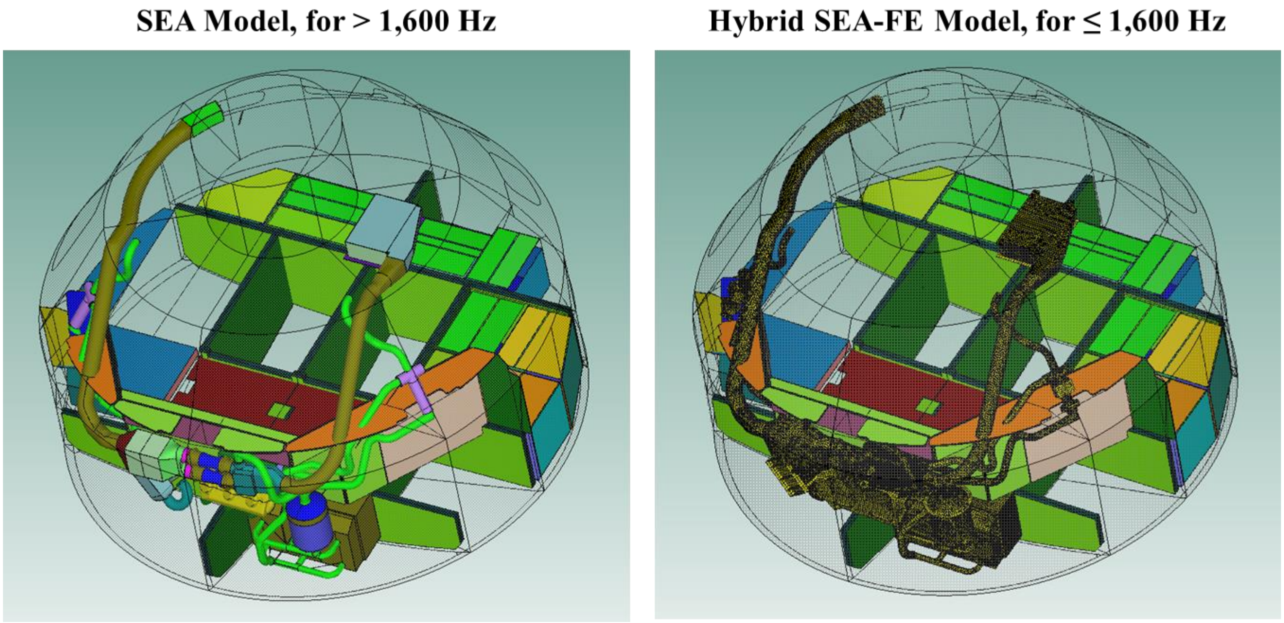
Source (Allen, 2015)
Figure 3: Acoustic levels measured on-orbit in ISS US Segment Modules.



Source (Allen, 2015)
Figure 4: Acoustic levels measured on-orbit in ISS US Crew Quarters with fans on high-flow setting.

The configuration of the Orion Multipurpose Crew Vehicle (MPCV) is similar to Apollo's Command Module, though much larger. Acoustic requirements for Orion are provided in the Human Systems Integration Requirements (NASA, 2014), and specify a continuous noise requirement of NC-52 for the vehicle, including payloads and GFE.

In order to achieve the NC-52 requirement inside Orion, extensive acoustic modelling was performed in a combined effort between NASA and the prime contractor. The modelling was performed using a Finite Element Method (FEM) for the low frequencies and Statistical Energy Analysis (SEA) for the high frequencies, with a hybrid technique to connect the two frequency ranges. This acoustic model was used to develop Sound Power Level (PWL) allocations for the noise sources, which included the cabin fan, two suit loop fans, and a water pump. In order to relieve some of the burden from this environmental control and life support (ECLS) system hardware, concerning acoustic requirements, system-level noise controls were designed into Orion;s crew cabin and were included in the acoustic model. These noise controls included acoustically absorptive blankets and sound blocking sealing to help contain the noise behind the "ECLS wall" behind which all of the ECLS equipment, i.e. fans and pumps, were located. These system-level noise controls provided approximately 9 dBA of noise reduction. Figure 5 shows the SEA acoustic model and the hybrid model.



Source (Chu, 2016)
Figure 4: Orion acoustic models.

In order to account for payloads and GFE, an allocation of NC-46 was reserved. This left approximately NC-50 for the Orion vehicle's continuous noise. The allocated acoustic requirements for Orion's continuous noise sources, i.e. fans and pumps, were developed by finding a sound pressure level solution of the acoustic model that was equal to the NC-50 curve. Idealized sound power levels were used as inputs, where the two suit loop fans were assumed to produce the same PWL, and the cabin fan PWL was determined by assuming that the same component noise control, i.e. inlet/outlet muffler, attenuations would be required for suit loop and cabin fans. Since water pump noise levels had been measured on the ground during an acoustic test of the Exploration Flight Test 1 (EFT-1) vehicle, sound power levels of the pump were developed from this test data and were used in the acoustic model for the pump acoustic inputs.

Once the idealized sound power allocations were determined, these allocations were used as inputs into FEM/SEA acoustic models of the various ECLS noise source end item hardware, in the configurations under which their sound power levels would be measured. This included test ductwork and an anechoic test environment. For each hardware end item, results from these models provided final inlet, outlet, and case-radiated sound power level allocated requirements. After measuring the sound power levels of the actual noise sources, using test set-ups that correspond to the end item acoustic models, comparisons with the developed allocations revealed the needed acoustic attenuation of the component noise controls, including inlet/outlet mufflers and fan casing wraps.

By developing noise source allocations, based on rigorous acoustic modelling efforts, system-level noise controls, and component noise controls developed based on comparing the modelling results with noise source development testing, it is hoped that Orion will meet its NC-50 allocation of the NC-52 requirement. Orion's continuous noise requirement will be verified by system level acoustic testing, after final assembly and prior to flight.

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